

**\*\*Volume Title\*\***

*ASP Conference Series, Vol. \*\*Volume Number\*\**

**\*\*Author\*\***

© **\*\*Copyright Year\*\*** *Astronomical Society of the Pacific*

## **Globular cluster systems of early-type galaxies - do we understand them?**

Tom Richtler

*Departamento de Astronomía, Universidad de Concepción, Barrio  
Universitario, Concepción, Chile*

**Abstract.** I review recent and less recent work on globular cluster systems in early-type galaxies. Explaining their properties and possible assembly scenarios, touches on a variety of astrophysical topics from cluster formation itself to galaxy formation and evolution and even details of observational techniques. The spectacular cluster systems of central galaxies in galaxy clusters may owe their richness to a plethora of less spectacular galaxies and their star formation processes. It seems that dwarf galaxies occupy a particularly important role.

### **1. Introduction - globular clusters and dwarf galaxies**

Talking about globular cluster systems with the intention to reach an audience of non-experts is a particular challenge because often, a specific discovery or result is sparkling brighter inside the cosmos of experts than outside, where the horizon is wider and sparks dim easily. On the other hand, the variety of astrophysical problems relevant to star cluster research (see the reviews of Brodie & Strader 2006, Harris 2010, and do not miss Kissler-Patig 2009) joins a large and explosive congregation, where sparks can have tremendous effects.

The formation of globular clusters (GCs) is yet to be understood in detail (as is usually the case with dissipative processes in astrophysics), but it is not a mystery. We see GCs today forming in a variety of galaxy types, most spectacularly in starbursts, triggered by galaxy interactions (e.g. Schweizer 2009). The origin of the most massive star cluster known, with a mass of  $8 \times 10^7 M_{\odot}$  (Maraston et al. 2004), W3 in the interacting galaxy NGC 7252, can be convincingly related to the starburst, which occurred 0.5 Gyr ago. Such massive objects may form by rapid merging of star cluster complexes (Fellhauer & Kroupa 2005; Kissler-Patig et al. 2006). Also in "normal" spiral galaxies, the formation of massive star clusters is supported by a high star-formation rate (Larsen & Richtler 2000). Integrating the cosmic star formation rate (e.g. Hopkins 2004), one finds that about 65% of all stellar mass has been formed before  $z=1$  (age 8.8 Gyr for a standard cosmology). In this epoch, the star formation rate was much higher than it is today, so most GCs in the Universe are old, but do not represent by nature the oldest populations. This "cosmic" argument does not apply to individual galaxies and many intermediate-age GCs have been found in early-type galaxies (e.g. Puzia et al. 2005).

Messier 92 is one of the best investigated Galactic GCs. Its age can currently be constrained to be  $11 \pm 1.5$  Gyr (di Cecco et al. 2010) ( $1.6 < z < 5$ ), and it is one of the metal-poorest clusters. An iron abundance of  $[\text{Fe}/\text{H}] = -2.3$  (Kraft & Ivans 2003) and

a mass of  $1.5 \times 10^5 M_\odot$  mean a total iron mass of only  $0.8 M_\odot$ , a mass, which can be produced by a few SNI supernovae. That there is no detectable star-to-star variation of the iron abundance (which is not the case for other elements, e.g. Angelou et al. 2012), permits the conclusion that M92 is not self-enriched and that it has formed in an already well-mixed environment. This environment cannot have been very massive since there is no significant field population with this iron abundance. If we call it a "dwarf galaxy" then we are close to the scenario proposed by Searle & Zinn (1978) who called these entities "protogalactic fragments".

Dwarf galaxies donate GCs to the Milky Way. This becomes manifest through the Sagittarius stream (Ibata et al. 2001; Siegel et al. 2011) and other candidates (e.g. Pawlowski et al. 2012 and references therein). Moreover, the "young halo clusters" trace the plane of Milky Way satellites (Yoon & Lee 2002; Kroupa et al. 2005; Keller et al. 2012). Forbes & Bridges (2010) estimate that an appreciable fraction of the Galactic GC system has been accreted through dwarf galaxies.

If accretion plays an important role for the assembly of the metal-poor part of relatively isolated spiral galaxies, what role does it occupy in really dense environments?

## 2. The richness of globular cluster systems

### 2.1. The richest globular cluster systems are not so rich

A popular quantitative measure for the richness of a globular cluster system (GCS) is the "specific frequency"  $S_N$ , which has been defined by (Harris & van den Bergh 1981) as  $S_N = N_{GC} 10^{0.4(M_V+15)}$ , where  $N_{GC}$  is the total number of GCs and  $M_V$  the host galaxy's absolute V-magnitude.

We find the richest GCSs in terms of GC number around central galaxies in galaxy clusters, the nearest being M87 (Virgo) (Tamura et al. 2006; Harris 2009b; Strader et al. 2011), NGC 1399 (Fornax) (Kissler-Patig et al. 1999; Richtler et al. 2004; Dirsch et al. 2003b; Schuberth et al. 2010), NGC 3311 (Hydra I) (Wehner et al. 2008; Richtler et al. 2011).  $S_N$ -values for these galaxies, which can host more than 10000 GCs, are somewhat uncertain, not so much for the number of GCs, but because  $M_V$  can be easily underestimated for these galaxies with very extended stellar halos. The case of NGC 3311 is illustrative, because this galaxy had the reputation of showing a particularly high  $S_N$ , e.g. McLaughlin et al. (1995) quoted  $S_N = 15 \pm 6$ . Wehner et al. (2008) found 16500 GCs within a radius of 150 kpc and adopted  $M_V = -22.8$ , thus  $S_N = 12.5$ , the uncertainties still permitting an extreme lower limit of  $S_N \approx 9$ . But integrating the V-luminosity profile of Richtler et al. (2011) out to the same radius results in  $M_V = -24$  and  $S_N = 4.1$ , which is a normal value for giant elliptical galaxies. A similar point has been made for NGC 1399 (Ostrov et al. 1998; Dirsch et al. 2003b). Therefore there is no hard evidence that  $S_N$ -values for central giant ellipticals are dramatically higher than for normal ellipticals.

Intuition tells us that accretion of dwarf galaxies for ellipticals in galaxy clusters should be even more important than for spiral galaxies (Cote et al. 1998 formulated this beyond intuition; see also Hilker et al. 1999). Clear evidence, e.g. in the form of streams, is only just now emerging, for example in the cases of M87 (Romanowsky et al. 2012) or NGC 3311 (Arnaboldi et al. 2012). The halos of these central galaxies have been built up by long-term accretion of material from the cluster environment, a process which is still on-going. Strong evidence for a significant growth of massive

elliptical galaxies since  $z=2$  (10.3 Gyr) has been provided by van Dokkum et al. (2010). They find that outside a core with a size of about 5kpc, elliptical galaxies increased their mass by a factor of 4 within the last 10 Gyr. This happens predominantly through minor and dry mergers (Tal et al. 2012). Obviously, GCSs should share the same fate.

For NGC 1399, kinematical data indicate that many GCs cannot have formed *in situ*. One finds in the GCS of NGC 1399 objects, which by their high radial velocities must reach apocentric distances of 500 kpc or even greater (Richtler et al. 2004; Schuberth et al. 2010). These few objects near their pericenters must trace a much larger (unknown) population with high space velocities, but low radial velocities. Their orbital velocities result from potential differences that exist within the Fornax cluster rather than within NGC 1399, so one may call them "intracluster GCs" (Kissler-Patig et al. 1999).

## 2.2. The poorest globular cluster systems can be the richest

The GCSs of early-type dwarf galaxies are as interesting as those of giant ellipticals. The highest specific frequency known is that of the Fornax dwarf spheroidal with 5 GCs ( $S_N \approx 30$ ). Are dwarf galaxies for some reason more efficient in forming GCs? Miller & Lotz (2007) indeed found a trend of increasing  $S_N$  with decreasing brightness of the host galaxy for dwarf ellipticals in Fornax, Virgo and the Leo group. The largest data base in this respect is the HST/ACS Virgo survey (Peng et al. 2008), in which about 100 early-type Virgo galaxies have been imaged down to a magnitude of  $M_V \approx -16$ . This work does not support a clear relation between  $S_N$  and host galaxy brightness, but dwarf galaxies fill a larger  $S_N$ -interval than giant ellipticals. Probably a key finding is that dwarf galaxies with large clustercentric distances consistently show low  $S_N$ -values, while high  $S_N$ -values are found among the (projected) inner dwarf galaxy population, i.e. among those galaxies with a higher probability of interactions, which may have triggered star-bursts.

## 3. The phenomenon of "bimodality"

The metallicity distribution of Galactic GCs is "bimodal", i.e. well represented by two Gaussians, with metal-rich and metal-poor GCs being the bulge and the halo clusters, respectively (Zinn 1985). Do we find a similar fundamental structure in the GCSs of elliptical galaxies?

In an influential paper, Ashman & Zepf (1992) explored the idea that GCs form in mergers and interactions of galaxies (see their introduction for the history of this concept) and hypothesized that the metallicity distribution of GCs in elliptical galaxies should be bimodal. Adopting the merger paradigm for elliptical galaxies, metal-poor clusters are the old GCs of the pre-merger components, while metal-rich clusters form in starbursts triggered by gas-rich mergers of spiral galaxies. This *prediction* of bimodality in the *color* distribution of GCs has indeed been found in many elliptical galaxies (e.g. Zepf & Ashman 1993; Whitmore et al. 1995; Gebhardt & Kissler-Patig 1999; Larsen et al. 2001; Kundu & Whitmore 2001; Peng et al. 2006; Harris et al. 2009; Harris 2009a). Studies in the Washington photometric system showed this bimodality particularly well (e.g. Geisler et al. 1996; Dirsch et al. 2003b,a; Bassino et al. 2006): it can be characterized by two Gaussians with peaks at  $C-R=1.35$  (the "blue" peak) and  $C-R=1.75$  (the "red" peak) (these peaks are not found in Fig.2!). The blue peak is remarkably constant among the investigated galaxies, while the red peak gets slightly

redder with increasing host galaxy brightness (see also Larsen & Richtler 2000). However, this color bimodality does not apply to the brightest clusters in some GCSs, which avoid very red and very blue colors.

The HST/ACS surveys in Virgo and the Fornax confirm this with a much larger database (Peng et al. 2006, 2008; Jordán et al. 2009). It turns out that bimodal color distributions are mainly a signature of bright host galaxies, which does not come as a surprise: early-type galaxies follow a well-defined color-magnitude relation (e.g. Smith Castelli et al. 2008; Misgeld et al. 2008) and one does not expect GCs to be redder than the host galaxy itself. A striking difference between the blue and red clusters is that the mean color of the red subpopulation strongly correlates with the host galaxy luminosity and thus with its color, while the mean color of blue clusters is more or less constant.

Blue and red GC populations, however, differ in more than only their colors. As shown in many papers, the radial number density profiles of red clusters are steeper and resemble more the light profile of their host galaxies. Accordingly, they show a lower velocity dispersion than the blue clusters. For NGC 1399, Fig.20 of Schuberth et al. (2010) demonstrates that the velocity dispersion exhibits a sudden change between red and blue clusters, not a smooth transition.

Do these bimodal color distributions reflect bimodal metallicity distributions? There had been some claims that a non-linearity of the color-metallicity relation, in combination with a considerable scatter around this relation, can produce a bimodal color distribution, even if the underlying metallicity distribution is not bimodal (Richtler 2006; Yoon et al. 2006). More recent work strengthens this point. Yoon et al. (2011b,a) derive GC metallicity distributions from a non-linear color-metallicity relation and show that the inferred metallicity distributions are rather single-peaked (I caution that their example NGC 4374 is a multiple SNIa host galaxy, see more remarks below). A further complicating point is that their color-metallicity relation becomes so insensitive to metallicity for clusters metal-poorer than about  $[\text{Fe}/\text{H}] = -1.5$ , that to infer a metallicity distribution from a color distribution seems to be only meaningful if color and metallicity are related without any generic scatter. But this is not the case, because metal-poor Galactic GCs having the same metallicity can show quite different CMDs (Fig.1). Therefore, the reconstructed metallicity distribution for metal-poor clusters might be considered as a mean distribution without saying much about an individual object. However, a weak metallicity-brightness relation for metal-poor clusters, as described by Harris (2009a), is expected, because massive clusters have a higher probability to originate from more massive host galaxies with an overall higher metallicity.

If IR-bands are included, bimodality may vanish almost completely, as shown by Blakeslee et al. (2012) for NGC 1399, and Chies-Santos et al. (2011, 2012) for a sample of 17 early-type galaxies. Galaxies with very pronounced blue peaks in g-z are NGC 4374 and NGC 4526. These galaxies hosted three and two SNIa events, respectively. Therefore, one may assume significant intermediate-age populations to be present, and probably also intermediate-age GCs, and the color is not anymore a pure metallicity indicator. More SNIa host galaxies in their sample are NGC 4382, NGC 4621, and NGC 4649. The striking deficiency of red clusters in NGC 4660 (which one also finds in the sample of Peng et al. (2006)) is remarkable. There may be more individuality among GCSs than previously thought. In those cases, where metallicities of larger GC samples have been derived from integrated spectra (not only of early-type galaxies!)

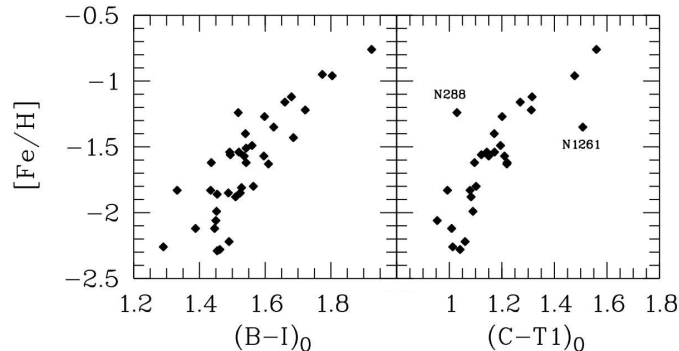


Figure 1. Colour-metallicity relations for Galactic GCs with reddenings less than  $E(B-V)=0.15$ , using B-I data from Harris (1996) and C-T1 data from Harris & Cantina (1977). The non-linearity is clearly seen. For clusters metal-poorer than about  $[Fe/H]=-1.5$ , the color becomes a very bad proxy for the metallicity, more so for B-I than for C-T1. Note, however, the large deviations for some clusters. Also note that these colors, measured with diaphragms, refer only to the innermost parts of GCs.

(Foster et al. 2010, 2011; Caldwell et al. 2011), the metallicity distributions appear unimodal with one broad peak around  $[Fe/H]=-1$ .

#### 4. Once more: giant and dwarf galaxies

The question to what degree  $S_N$ -values of galaxies reflect the efficiency of GC formation is difficult to answer (relating GC masses to host galaxy mass as do e.g. Peng et al. 2008; Georgiev et al. 2010 would be more physical, but observationally more difficult to determine). Although the  $S_N$ -values of central galaxies may not be as high as previously thought, they are still higher than elliptical galaxies of lower luminosity. The ACS Virgo survey (Peng et al. 2008) reveals a shallow minimum around  $M_V \approx -20$ , but without a well-defined relation for the dwarf or for the giant regime, although many dwarf galaxies as faint as  $M_V = -16$  show  $S_N$ -values rivalling or exceeding typical values for giant galaxies. Including fainter galaxies from Lotz et al. (2004) lets the trend of increasing  $S_N$  with decreasing luminosity appears clearer: values higher than 10 are normal, particularly for nucleated dwarf galaxies.

This is also visible in the compilation of Georgiev et al. (2010). They embed the variation of  $S_N$ -values in the context of galaxy formation, inspired by Dekel & Birnboim (2006) (see Forbes 2005 for an earlier account). In brief, star formation in low mass galaxies is regulated by stellar feedback, in high mass galaxies by virial shocks, which in both regimes leads to a suppression of field star formation, and favors star clusters. One notes that this interpretation implies an alternative view: here it is a generic property of star formation processes in giant ellipticals, which produces the rich GCSs, not the infall of less massive galaxies with intrinsically higher  $S_N$ -values. It may be, however, difficult to defend this view in front of all evidence for the role of accretion. Starbursts in dwarf galaxies might hold the key for a proper understanding.

Can metallicity itself be a parameter for efficient GC formation? At low metallicity, the energy and momentum input into the interstellar medium via radiation-driven

stellar winds is reduced (Kudritzki 2002), leading to a higher star formation efficiency (Dib et al. 2011). Glover & Clark (2012a) find that molecules are not necessarily a prerequisite for star formation, but that dust is an important ingredient for cooling processes. Star formation occurs in cold gas at higher temperatures, and Jeans masses are increased (Glover & Clark 2012b). The formation of dense substructures in a collapsing cloud is efficiently suppressed at low metallicities, because turbulence cannot create clumps as efficiently as in high-metallicity clouds (Glover & Clark 2012b). This may lead to a more coherent star formation inside a star-forming cloud. These are all factors which support the dynamical stability of star-forming clouds, and plausibly favor the formation of compact and coherent structures, which lead to the extremely clustered star formation for example in Blue Compact Galaxies (e.g. Adamo et al. 2011).

## 5. Globular clusters outside galaxies

“Cosmological” formation of GCs, i.e. GCs embedded in a dark halo, is interesting to imagine, but difficult to prove. GCs apparently exist outside galaxies, however, this does not mean that they were formed outside galaxies. The objects with high radial velocities around central galaxies spend most of their orbital life far away from the cluster center. But there are also GC populations in galaxy clusters without a central galaxy. West et al. (2011) found in a population of intergalactic GCs in Abell 1185, mostly metal-poor. A recent survey with HST/ACS of the Coma cluster uncovered a huge population of GCs, filling the entire cluster core (Peng et al. 2011). The authors estimate a total of about 47000 GCs out to a radius of 570 kpc. Dissolution of dwarf galaxies and tidal stripping from more massive galaxies might both contribute to create this largest GCS in the local Universe.

## 6. Isolated elliptical galaxies

Suspecting dwarf galaxies as donors of metal-poor GCs, it would be interesting to compare cluster galaxies with isolated elliptical galaxies. Unfortunately, the data are sparse. After the compilation of Spitler et al. (2008), no new work on isolated ellipticals has been reported, leaving NGC 720 (Kissler-Patig et al. 1996) and NGC 821 (Spitler et al. 2008) as prototypes. Both present relatively poor cluster systems. However, many “isolated ellipticals” exhibit tidally disturbed features and may be in fact late mergers (Tal et al. 2009), including NGC 720 that does not exhibit obvious morphological peculiarities, but strong population gradients (Rembold et al. 2005).

## 7. NGC 1316 - cluster formation in a late merger

A galaxy whose brightness is dominated by intermediate-age populations (Kuntschner 2000), is the merger remnant NGC 1316 (Fornax A) in the outskirts of the Fornax galaxy cluster. It might illustrate the processes that were in action during the youth of giant ellipticals to form metal-rich clusters (see Richtler et al. 2012a for references). It experienced a major starburst about 2-3 Gyr ago that produced many massive star clusters, the brightest one (114 in the list of Goudfrooij et al. 2001a) having a mass of the order  $2 \times 10^7 M_{\odot}$ . Note that Brodie et al. (2011) would not call it an “Ultra Compact Dwarf”, because its effective radius is smaller than 10 pc (Goudfrooij 2012).

The imprint of the 2 Gyr starburst is a well defined peak in the color distribution of GCs (Richtler et al. 2012a) (Fig.2). Cluster ages from integrated spectra have been determined only for a few of the brightest clusters (Goudfrooij et al. 2001b), but the colors (with the assumption of solar metallicity for all bright clusters) fit well to these ages. Star formation continued after this starburst and a second peak corresponds to 0.8 Gyr (which still has to be confirmed by spectroscopy). We find GCs with ages as young as 0.5 Gyr. Including fainter clusters probably samples older objects and lets these peaks largely disappear. A very interesting observation is that the brightest clusters seem to avoid the systemic radial velocity of NGC 1316 by showing large negative offsets up to 500 km/s. This indicates elongated orbits and a population of massive clusters far away from the center, which still has to be identified. The starburst seem to have happened in a very early stage of the merger with the merger components still separated with high relative velocities.

Very remarkable is the object SH2, discovered by Schweizer (1980). Rather than as a normal HII-region, it appears as an ensemble of star clusters with ages around 0.1 Gyr (Richtler et al. 2012b). Its exact nature still awaits investigation, but a plausible hypothesis is that of an infalling dwarf galaxy, having recently experienced a starburst. In this case, one would expect low metallicities and it would constitute an example, how metal-poor clusters are donated to a GCS.

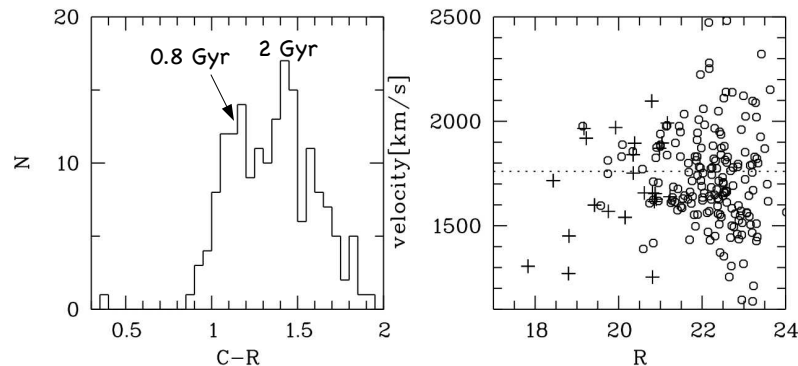


Figure 2. Left panel: color histogram of 178 confirmed GCs in NGC 1316 (Richtler et al., in preparation). The ages assume solar metallicity. Right panel: radial velocities vs.  $R$ -magnitudes for the same clusters augmented by a sample from Goudfrooij et al. (2001b) (crosses). Note, how the bright cluster population avoids the systemic velocity (dashed line) and how the velocity dispersion increases with fainter magnitudes.

## 8. Inventory

A cautiously positive answer to the title question seems to be appropriate. A description of a global picture (which generously ignores details) can be: giant elliptical galaxies assembled their metal-poor GCs by the accretion of dwarf galaxies. The metal-rich GCs formed in early starbursts, triggered by gas-rich mergers. Whether colors alone can provide an adequate description of the substructure of an GCS, has become doubtful. With

higher precision of kinematical data, more substructures in GCSs will be detected and perhaps single merger events can be identified. The key to all that is the physics of star cluster formation in starbursts, whether in dwarf galaxies or in massive systems. Modern simulations of galaxy mergers now resolve star cluster scales (see Hopkins et al. 2012 and references therein) and will probably provide the physical understanding.

**Acknowledgments.** My cordial thanks go to the organizers of this great conference, during which I learned once again to admire the astronomy coming out of Utrecht. I thank Soeren S. Larsen for helpful remarks on the present article and for much more. I am grateful to Richard Lane for a critical reading of the text. I also acknowledge the financial support from the Chilean Center for Astrophysics, FONDAF Nr. 15010003, FONDECYT project Nr. 1100620, and through the BASAL Centro de Astrofísica y Tecnologías Afines (CATA) PFB-06/2007.

## References

- Adamo, A., Östlin, G., & Zackrisson, E. 2011, MNRAS, 417, 1904. 1107.0725
- Angelou, G. C., Stancliffe, R. J., Church, R. P., Lattanzio, J. C., & Smith, G. H. 2012, ApJ, 749, 128. 1202.2859
- Arnaboldi, M., Ventimiglia, G., Iodice, E., Gerhard, O., & Coccato, L. 2012, ArXiv e-prints. 1205.5289
- Ashman, K. M., & Zepf, S. E. 1992, ApJ, 384, 50
- Bassino, L. P., Richtler, T., & Dirsch, B. 2006, MNRAS, 367, 156. arXiv:astro-ph/0511770
- Blakeslee, J. P., Cho, H., Peng, E. W., Ferrarese, L., Jordán, A., & Martel, A. R. 2012, ApJ, 746, 88. 1201.1031
- Brodie, J. P., Romanowsky, A. J., Strader, J., & Forbes, D. A. 2011, AJ, 142, 199. 1109.5696
- Brodie, J. P., & Strader, J. 2006, ARA&A, 44, 193. arXiv:astro-ph/0602601
- Caldwell, N., Schiavon, R., Morrison, H., Rose, J. A., & Harding, P. 2011, AJ, 141, 61. 1101.3779
- Chies-Santos, A. L., Larsen, S. S., Cantiello, M., Strader, J., Kuntschner, H., Wehner, E. M., & Brodie, J. P. 2012, A&A, 539, A54. 1201.3649
- Chies-Santos, A. L., Larsen, S. S., Kuntschner, H., Anders, P., Wehner, E. M., Strader, J., Brodie, J. P., & Santos, J. F. C. 2011, A&A, 525, A20. 1010.4801
- Cote, P., Marzke, R. O., & West, M. J. 1998, ApJ, 501, 554. arXiv:astro-ph/9804319
- Dekel, A., & Birnboim, Y. 2006, MNRAS, 368, 2. arXiv:astro-ph/0412300
- di Cecco, A., Becucci, R., Bono, G., Monelli, M., Stetson, P. B., Degl’Innocenti, S., Prada Moroni, P. G., Nonino, M., Weiss, A., Buonanno, R., Calamida, A., Caputo, F., Corsi, C. E., Ferraro, I., Iannicola, G., Pulone, L., Romaniello, M., & Walker, A. R. 2010, PASP, 122, 991. 1006.5217
- Dib, S., Piau, L., Mohanty, S., & Braine, J. 2011, MNRAS, 415, 3439. 1102.3839
- Dirsch, B., Richtler, T., & Bassino, L. P. 2003a, A&A, 408, 929. arXiv:astro-ph/0307200
- Dirsch, B., Richtler, T., Geisler, D., Forte, J. C., Bassino, L. P., & Gieren, W. P. 2003b, AJ, 125, 1908. arXiv:astro-ph/0301223
- Fellhauer, M., & Kroupa, P. 2005, MNRAS, 359, 223. arXiv:astro-ph/0502086
- Forbes, D. A. 2005, ApJ, 635, L137. arXiv:astro-ph/0511291
- Forbes, D. A., & Bridges, T. 2010, MNRAS, 404, 1203. 1001.4289
- Foster, C., Forbes, D. A., Proctor, R. N., Strader, J., Brodie, J. P., & Spitler, L. R. 2010, AJ, 139, 1566. 1002.1107
- Foster, C., Spitler, L. R., Romanowsky, A. J., Forbes, D. A., Pota, V., Bekki, K., Strader, J., Proctor, R. N., Arnold, J. A., & Brodie, J. P. 2011, MNRAS, 415, 3393. 1104.5503
- Gebhardt, K., & Kissler-Patig, M. 1999, AJ, 118, 1526. arXiv:astro-ph/9906499
- Geisler, D., Lee, M. G., & Kim, E. 1996, AJ, 111, 1529
- Georgiev, I. Y., Puzia, T. H., Goudfrooij, P., & Hilker, M. 2010, MNRAS, 406, 1967. 1004.2039



- Glover, S. C. O., & Clark, P. C. 2012a, MNRAS, 421, 9. 1105.3073  
 — 2012b, ArXiv e-prints. 1203.4251
- Goudfrooij, P. 2012, ApJ, 750, 140. 1203.1242
- Goudfrooij, P., Alonso, M. V., Maraston, C., & Minniti, D. 2001a, MNRAS, 328, 237. arXiv:astro-ph/0107533
- Goudfrooij, P., Mack, J., Kissler-Patig, M., Meylan, G., & Minniti, D. 2001b, MNRAS, 322, 643. arXiv:astro-ph/0010275
- Harris, H. C., & Canterna, R. 1977, AJ, 82, 798
- Harris, W. E. 1996, AJ, 112, 1487  
 — 2009a, ApJ, 699, 254. 0904.4208  
 — 2009b, ApJ, 703, 939. 0908.1120  
 — 2010, Royal Society of London Philosophical Transactions Series A, 368, 889. 0911.0798
- Harris, W. E., Kavelaars, J. J., Hanes, D. A., Pritchett, C. J., & Baum, W. A. 2009, AJ, 137, 3314. 0811.1437
- Harris, W. E., & van den Bergh, S. 1981, AJ, 86, 1627
- Hilker, M., Infante, L., & Richtler, T. 1999, A&AS, 138, 55. arXiv:astro-ph/9905112
- Hopkins, A. M. 2004, ApJ, 615, 209. arXiv:astro-ph/0407170
- Hopkins, P. F., Cox, T. J., Hernquist, L., Narayanan, D., Hayward, C. C., & Murray, N. 2012, ArXiv e-prints. 1206.0011
- Ibata, R., Irwin, M., Lewis, G. F., & Stolte, A. 2001, ApJ, 547, L133. arXiv:astro-ph/0004255
- Jordán, A., Peng, E. W., Blakeslee, J. P., Côté, P., Eyheramendy, S., Ferrarese, L., Mei, S., Tonry, J. L., & West, M. J. 2009, ApJS, 180, 54
- Keller, S. C., Mackey, D., & Da Costa, G. S. 2012, ApJ, 744, 57. 1109.4414
- Kissler-Patig, M. 2009, Open Questions in the Globular Cluster - Galaxy Connection, 1
- Kissler-Patig, M., Grillmair, C. J., Meylan, G., Brodie, J. P., Minniti, D., & Goudfrooij, P. 1999, AJ, 117, 1206. arXiv:astro-ph/9811373
- Kissler-Patig, M., Jordán, A., & Bastian, N. 2006, A&A, 448, 1031. arXiv:astro-ph/0512360
- Kissler-Patig, M., Richtler, T., & Hilker, M. 1996, A&A, 308, 704
- Kraft, R. P., & Ivans, I. I. 2003, PASP, 115, 143. arXiv:astro-ph/0210590
- Kroupa, P., Theis, C., & Boily, C. M. 2005, A&A, 431, 517. arXiv:astro-ph/0410421
- Kudritzki, R. P. 2002, ApJ, 577, 389. arXiv:astro-ph/0205210
- Kundu, A., & Whitmore, B. C. 2001, AJ, 121, 2950. arXiv:astro-ph/0103021
- Kuntschner, H. 2000, MNRAS, 315, 184
- Larsen, S. S., Brodie, J. P., Huchra, J. P., Forbes, D. A., & Grillmair, C. J. 2001, AJ, 121, 2974. arXiv:astro-ph/0102374
- Larsen, S. S., & Richtler, T. 2000, A&A, 354, 836. arXiv:astro-ph/0001198
- Lotz, J. M., Miller, B. W., & Ferguson, H. C. 2004, ApJ, 613, 262. arXiv:astro-ph/0406002
- Maraston, C., Bastian, N., Saglia, R. P., Kissler-Patig, M., Schweizer, F., & Goudfrooij, P. 2004, A&A, 416, 467. arXiv:astro-ph/0311232
- McLaughlin, D. E., Secker, J., Harris, W. E., & Geisler, D. 1995, AJ, 109, 1033
- Miller, B. W., & Lotz, J. M. 2007, ApJ, 670, 1074. 0708.2511
- Misgeld, I., Mieske, S., & Hilker, M. 2008, A&A, 486, 697. 0806.0621
- Ostrov, P. G., Forte, J. C., & Geisler, D. 1998, AJ, 116, 2854
- Pawlowski, M. S., Pflamm-Altenburg, J., & Kroupa, P. 2012, MNRAS, 299, 1204. 5176
- Peng, E. W., Ferguson, H. C., Goudfrooij, P., Hammer, D., Lucey, J. R., Marzke, R. O., Puzia, T. H., Carter, D., Balcells, M., Bridges, T., Chiboucas, K., del Burgo, C., Graham, A. W., Guzmán, R., Hudson, M. J., Matković, A., Merritt, D., Miller, B. W., Mouhcine, M., Philipps, S., Sharples, R., Smith, R. J., Tully, B., & Verdoes Kleijn, G. 2011, ApJ, 730, 23. 1101.1000
- Peng, E. W., Jordán, A., Côté, P., Blakeslee, J. P., Ferrarese, L., Mei, S., West, M. J., Merritt, D., Milosavljević, M., & Tonry, J. L. 2006, ApJ, 639, 95. arXiv:astro-ph/0509654
- Peng, E. W., Jordán, A., Côté, P., Takamiya, M., West, M. J., Blakeslee, J. P., Chen, C.-W., Ferrarese, L., Mei, S., Tonry, J. L., & West, A. A. 2008, ApJ, 681, 197. 0803.0330

- Puzia, T. H., Kissler-Patig, M., Thomas, D., Maraston, C., Saglia, R. P., Bender, R., Goudfrooij, P., & Hempel, M. 2005, *A&A*, 439, 997. [arXiv:astro-ph/0505453](#)
- Rembold, S. B., Pastoriza, M. G., & Bruzual, G. 2005, *A&A*, 436, 57
- Richtler, T. 2006, *Bulletin of the Astronomical Society of India*, 34, 83. [arXiv:astro-ph/0512545](#)
- Richtler, T., Bassino, L. P., Dirsch, B., & Kumar, B. 2012a, eprint [arXiv:1203.1879](#). 1203.1879
- Richtler, T., Dirsch, B., Gebhardt, K., Geisler, D., Hilker, M., Alonso, M. V., Forte, J. C., Grebel, E. K., Infante, L., Larsen, S., Minniti, D., & Rejkuba, M. 2004, *AJ*, 127, 2094. [arXiv:astro-ph/0401175](#)
- Richtler, T., Kumar, B., Bassino, L. P., Dirsch, B., & Romanowsky, A. J. 2012b, eprint [arXiv:1203.2463](#). 1203.2463
- Richtler, T., Salinas, R., Misgeld, I., Hilker, M., Hau, G. K. T., Romanowsky, A. J., Schuberth, Y., & Spolaor, M. 2011, *A&A*, 531, A119. 1103.2053
- Romanowsky, A. J., Strader, J., Brodie, J. P., Mihos, J. C., Spitler, L. R., Forbes, D. A., Foster, C., & Arnold, J. A. 2012, *ApJ*, 748, 29. 1112.3959
- Schuberth, Y., Richtler, T., Hilker, M., Dirsch, B., Bassino, L. P., Romanowsky, A. J., & Infante, L. 2010, *A&A*, 513, A52. 0911.0420
- Schweizer, F. 1980, *ApJ*, 237, 303
- 2009, *Globular Cluster Formation in Mergers*, 331
- Searle, L., & Zinn, R. 1978, *ApJ*, 225, 357
- Siegel, M. H., Majewski, S. R., Law, D. R., Sarajedini, A., Dotter, A., Marín-Franch, A., Chaboyer, B., Anderson, J., Aparicio, A., Bedin, L. R., Hempel, M., Milone, A., Paust, N., Piotto, G., Reid, I. N., & Rosenberg, A. 2011, *ApJ*, 743, 20. 1108.6276
- Smith Castelli, A. V., Bassino, L. P., Richtler, T., Cellone, S. A., Aruta, C., & Infante, L. 2008, *MNRAS*, 386, 2311. 0803.1630
- Spitler, L. R., Forbes, D. A., Strader, J., Brodie, J. P., & Gallagher, J. S. 2008, *MNRAS*, 385, 361. 0712.1382
- Strader, J., Romanowsky, A. J., Brodie, J. P., Spitler, L. R., Beasley, M. A., Arnold, J. A., Tamura, N., Sharples, R. M., & Arimoto, N. 2011, *ApJS*, 197, 33. 1110.2778
- Tal, T., van Dokkum, P. G., Nelán, J., & Bezanson, R. 2009, *AJ*, 138, 1417. 0908.1382
- Tal, T., Wake, D. A., van Dokkum, P. G., van den Bosch, F. C., Schneider, D. P., Brinkmann, J., & Weaver, B. A. 2012, *ApJ*, 746, 138. 1108.1392
- Tamura, N., Sharples, R. M., Arimoto, N., Onodera, M., Ohta, K., & Yamada, Y. 2006, *MNRAS*, 373, 601. [arXiv:astro-ph/0609070](#)
- van Dokkum, P. G., Whitaker, K. E., Brammer, G., Franx, M., Kriek, M., Labbé, I., Marchesini, D., Quadri, R., Bezanson, R., Illingworth, G. D., Muzzin, A., Rudnick, G., Tal, T., & Wake, D. 2010, *ApJ*, 709, 1018. 0912.0514
- Wehner, E. M. H., Harris, W. E., Whitmore, B. C., Rothberg, B., & Woodley, K. A. 2008, *ApJ*, 681, 1233. 0802.1723
- West, M. J., Jordán, A., Blakeslee, J. P., Côté, P., Gregg, M. D., Takamiya, M., & Marzke, R. O. 2011, *A&A*, 528, A115. 1101.5399
- Whitmore, B. C., Sparks, W. B., Lucas, R. A., Macchetto, F. D., & Biretta, J. A. 1995, *ApJ*, 454, L73
- Yoon, S.-J., Lee, S.-Y., Blakeslee, J. P., Peng, E. W., Sohn, S. T., Cho, J., Kim, H.-S., Chung, C., Kim, S., & Lee, Y.-W. 2011a, *ApJ*, 743, 150. 1109.5178
- Yoon, S.-J., & Lee, Y.-W. 2002, *Science*, 297, 578. [arXiv:astro-ph/0207607](#)
- Yoon, S.-J., Sohn, S. T., Lee, S.-Y., Kim, H.-S., Cho, J., Chung, C., & Blakeslee, J. P. 2011b, *ApJ*, 743, 149. 1109.5174
- Yoon, S.-J., Yi, S. K., & Lee, Y.-W. 2006, *Science*, 311, 1129. [arXiv:astro-ph/0601526](#)
- Zepf, S. E., & Ashman, K. M. 1993, *MNRAS*, 264, 611
- Zinn, R. 1985, *ApJ*, 293, 424